Reprinted from JOURNAL OF APPLIED METEOROLOGY, Vol. 9, No. 3, June, 1970, pp. 396–400
American Meteorological Society
Printed in U. S. A.

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(Manuscript received 22 October 1969, in revised form 20 February 1970)

ABSTRACT

Vertical mean wind profiles, hot-film data, and wave height data measured during the passage of an artificial sea slick are compared with similar measurements without a sea slick.

The effects of the slick are modifications of profile roughness length z_0, and a possible increase in mean wind speed. Power spectral density plots of wave records obtained before, during and after the slick show wave energy modifications for wavelengths up to 10 m. Coherence values computed from a cross-spectral density of the wind field and simultaneously measured wave field both during and after the slick demonstrate the importance of small waves to air-sea interaction processes. Phase angles indicate the maximum horizontal velocity occurs over the wave trough for all spectral components, some of which are above and some below the wind-wave "matched layer." During a slick, however, the horizontal velocity maximum occurs over the wave crest for those waves remaining coherent with the wind field.

1. Introduction

It is well known that oil calms waves. The combination of an ongoing air-sea interaction experiment and the availability of bio-degradable slick-forming material allowed an investigation of this phenomenon without causing pollution. The experiment was carried out as a cooperative effort of the Naval Research Laboratory and the Massachusetts Institute of Technology.

The experiment furnishes another example of how modification of the boundary dynamics affects a turbulent boundary layer, and looks at some of the processes which are occurring at the air-sea interface under unusual conditions.

2. The experiment

An artificially formed sea slick was spread over the ocean surface upwind of a fixed measurement site, and allowed to drift over the water in the vicinity of the measurement site. The instrument platform consisted of a rigid spar erected in 60 ft of water at the entrance to Buzzards Bay, Mass. The prevailing SW winds had a long overwater trajectory, giving a sea surface typical of deep-water waves. The nearest land upwind of the site was Block Island, 26 mi distant.

Five cup anemometers were arranged in a vertical array at 1, 2, 3, 5 and 8 m above the mean water surface to provide wind profile data. Two hot-film probes arranged in an x-array were mounted at 1 m, and a capacitance wave gage was mounted directly below the hot-film probes. The probe outputs represented the component wind velocity through the relations

$$\left.\begin{aligned} U&=K_1(V_A+V_B)\\ W&=K_2(V_A-V_B)\end{aligned}\right\}, \tag{1}$$

where U and W are the horizontal and vertical wind velocities, respectively, V_A and V_B the respective voltage outputs from anemometers A and B, and K_1 and K_2 scaling values representing the probe response characteristics. In practice K_1 and K_2 were determined by direct comparison of the $\bar{U}$ velocity with that speed sensed by an accurate cup anemometer mounted near the sensors, providing *in situ* probe calibration. The pyrex-backed, quartz-insulated sensing element of the hot-film probe has high directional sensitivity, mechanical rigidity, and electrical integrity, making it highly suited for field use. Probe alignment with the true vertical was accomplished by electrically adjusting the levels of V_A and V_B such that

$$\bar{W}=0. \tag{2}$$

Since the probes are suspended over a horizontal water surface, the use of this condition minimizes probe alignment errors such as those discussed by Kraus (1968).

The data from the measuring instruments were recorded simultaneously on an 8-channel tape recorder, then converted into a digital format for processing on an IBM-360 computer.

The weather conditions were favorable for observations. During the two days of tests the weather was un-

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and squally with passing rain showers. The mean speed varied between 5 and 10 m sec^{-1} on the day, for example. The water surface was covered hitecaps before the slick was added.

e monomolecular surface film

spontaneously-spreading, film-forming chemical, alcohol (9-octadecen-1-ol, cis-isomer), was used in xperiment. This liquid was selected because of its y, as demonstrated by Barger and Garrett (1968), et the criteria for a durable surface film capable of cing large modifications of surface properties. alcohol, a chemically unsaturated fatty alcohol, a rapidly spreading coherent monomolecular film eacts very slowly with sea water, if at all.

urface film of area 0.5 km^2 was produced by disg 13.2 liters of oleyl alcohol sprayed in droplets to strips, from a motor boat running a cross-wind rn 1 km upwind of the instrument tower. The film merged within minutes into a rectangular conus sea slick approximately 1.0 km×0.5 km, with ng axis aligned with the wind direction.

e chemical could have been dispersed from a single ion and in time an area of the surface would have covered by spreading of the surface active ma-l. However, experience in producing artificial sea s has shown that in order to cover a large area of ed shape rapidly, the film material must be put out prayed drops from a fast moving platform. The omolecular surface films from individual drops then e quickly to form a coherent slick. The drops of read liquid remained in equilibrium with the mono-r, forming reservoirs which could rapidly repair pors of the film lost to the destructive processes of wave n, dissipation, dissolution, evaporation, etc. Thus, surface tension decreases (film pressure) and other llary effects were near maximum in the treated area.

Data analysis

or initial wind analysis, the observed 10-min wind ile data were compared with the theoretical logamic profile

$$U(z)=\frac{U_*}{\kappa}\ln\left(\frac{z}{z_0}\right), \qquad (3)$$

re $U(z)$ is the wind velocity at height z, U_* the fric-velocity, z_0 the roughness length, and κ von rmán's constant. Objectivity in the analysis of the d data was accomplished by fitting the logarithmic d profile form to the observed profile points using t-squares fitting as discussed by Ruggles (1970). ce the specific profile form for each profile was known, profile parameters were computed. In all but one e the logarithmic profile approximation of the obved profile resulted in linear correlation coefficients

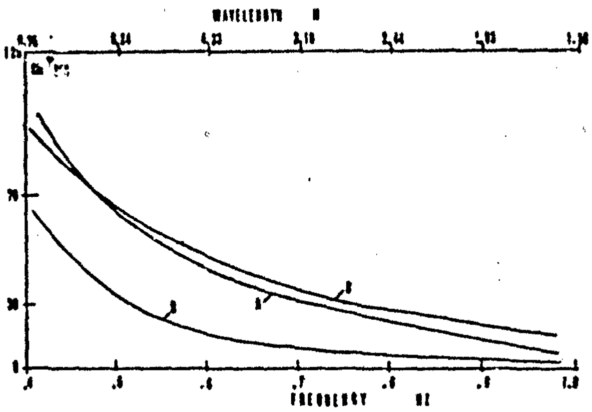

FIG. 1. Analog spectrum of high-frequency ocean wave energy computed before slick, A, during slick, B, and after passage of slick, C.

ranging from 1.00 to 0.85, thus justifying the use of the logarithmic profile as an approximation.

The experiments were conducted on two separate days. On each day data were collected showing conditions before, during and after the passage of the slick. Profile analysis was conducted using both days' data. Spectral analysis was performed using data only from 14 August 1968 due to instrumentation problems on the prior day.

Since we were concerned with locally-generated wind waves, the wave spectrum was computed by standard analog techniques for the high-frequency components of the waves, using wave height data passed through a high-pass filter and a waveform analyzer. Fig. 1A represents the analog wave spectrum for waves measured before the slick, Fig. 1B for waves in the slick just before the slick cleared the measurement site, and 1C after the slick had well cleared the measurement site.

To show air-sea interaction processes, cross-spectral analysis is used. Following Bendat and Piersol (1966), the cross-spectral density function for any two variables, m_1 and m_2, can be written as

$$S_{m_1m_2}(f)=\int_{-\infty}^{\infty}[m_1(t)m_2(t+\tau)]e^{-i2\pi f\tau}d\tau, \qquad (4)$$

where $S_{m_1m_2}(f)$ is the spectral density for variables m_1 and m_2 and is a function of the frequency f; it is a complex quantity and can be represented in the polar format

$$S_{m_1m_2}(f)=G_{m_1m_2}(f)e^{i\theta}, \qquad (5)$$

where $G_{m_1m_2}$ is a real quantity representing the absolute value of $S_{m_1m_2}$ and θ is the phase angle measured from the m_1 vector to m_2. The coherence function $\phi_{m_1m_2}$, is then defined as

$$\phi_{m_1m_2}(f)=\frac{G_{m_1m_2}(f)}{[G_{m_1m_1}(f)G_{m_2m_2}(f)]^{\frac{1}{2}}}, \qquad (6)$$

where $\phi_{m_1m_2}$ has a value between 0 and 1, and can be thought of as a correlation coefficient between selected

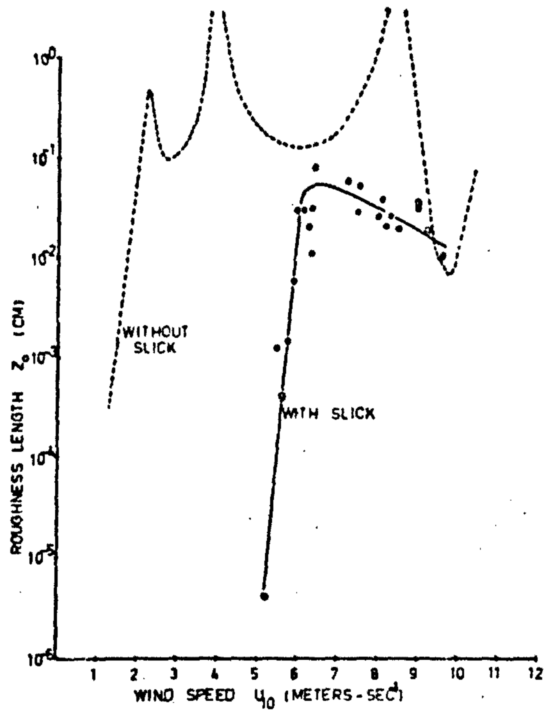

Fig. 2. Roughness lengths computed from measurements made over sea slicks (solid line) as compared to the average non-slick roughness lengths measured at the same site by Ruggles (dotted line).

spectral components of variables m_1 and m_2. The angle θ gives the phase relationship of the selected spectral components.

Coherence functions have been computed relating the horizontal wind velocity U with the wave height η and the vertical velocity W with wave height. Computation of the cross-spectral density function relating the horizontal velocity with the vertical velocity provides a spectral profile of Reynolds stress in the atmosphere directly above the ocean surface.

Table 1. Average roughness length and wind velocity.

Comment	z_0 (cm)	$\bar{U}$ (10 m) (m sec^{-1})	Averaging time (min)
	13 August 1968		
No slick	0.059	7.5	100
Slick	0.019	8.5	70
No slick	0.029	7.8	50
	14 August 1968		
No slick	0.196	4.2	40
Slick	0.029	5.6	60

5. Results

A total absence of capillary waves and breaking waves was observed within the slick. At the upwind edge of the slick, an abrupt change in the sea surface was noted, where the oil in the slick changed suddenly into the dark, rough appearance typical of a wind sea during a blustery day, with many breaking waves.

Fig. 2 shows the surface roughness z_0 as a function of horizontal wind speed at a height of 10 m, $U(10)$. The dotted line is the value of z_0 determined from data obtained in the absence of a slick (see Ruggles, 1970) and is based on 299 wind profile observations obtained at the same site. The circles represent observations over slicks, measured during the two days of slick experiments.

Table 1 summarizes the wind speed and average roughness length measured before, during and after the

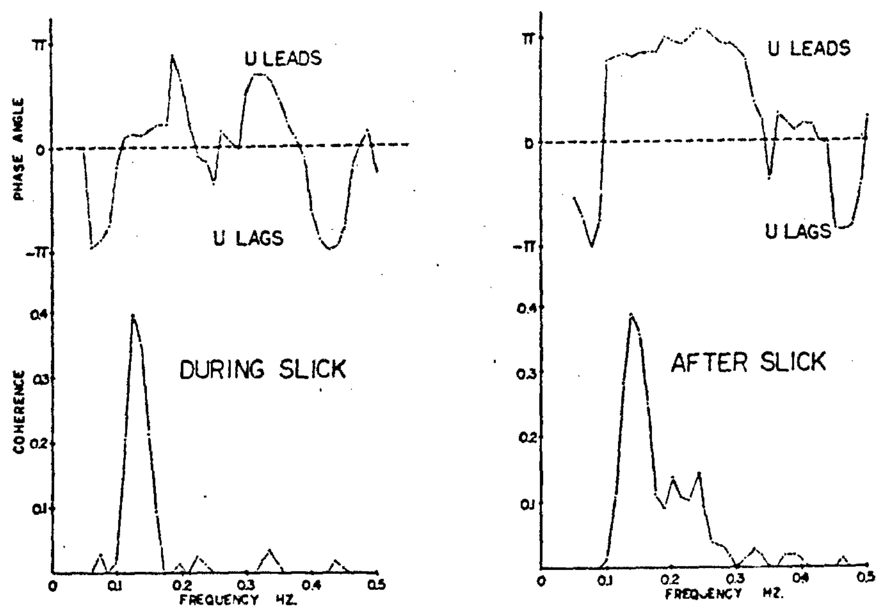

Fig. 3. Cross-spectral density U vs η.

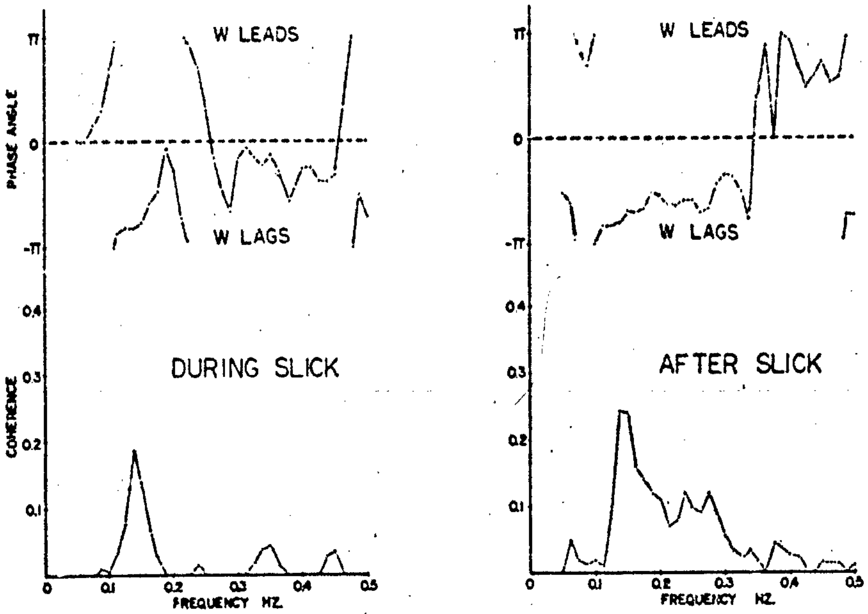

FIG. 4. Cross-spectral density W vs η.

assage of the slick. In the mean, during the passage of he slick, the roughness length decreased while the mean vind speed appeared to increase. From Fig. 1 we have dready noted the reduction of wave energy at high requencies (greater than 0.3 Hz) as the slick persists.

For spectral comparisons, we compared the wind ield over the ocean during the time the sea slick was n the vicinity of the measurement site with the wind ield observed after the slick had passed. The cross-pectral density or coherence was computed for the ollowing variables measured during and after the pas-age of the artificial sea slick: 1) coherence between horizontal velocity U vs wave height η, 2) coherence between vertical velocity W vs wave height η, and 3) cross-spectral density between horizontal velocity U vs vertical velocity W (Reynolds stress).

Plots of these data are displayed in Figs. 3–5. For all plots the spectral bandwidth is 0.025 Hz, and the standard error of estimate is 0.10 with 100 degrees of freedom. These plots indicate:

1) The coherence between the long-wave (low frequency) components of the sea and the wind field is modified only slightly, if at all, by the presence

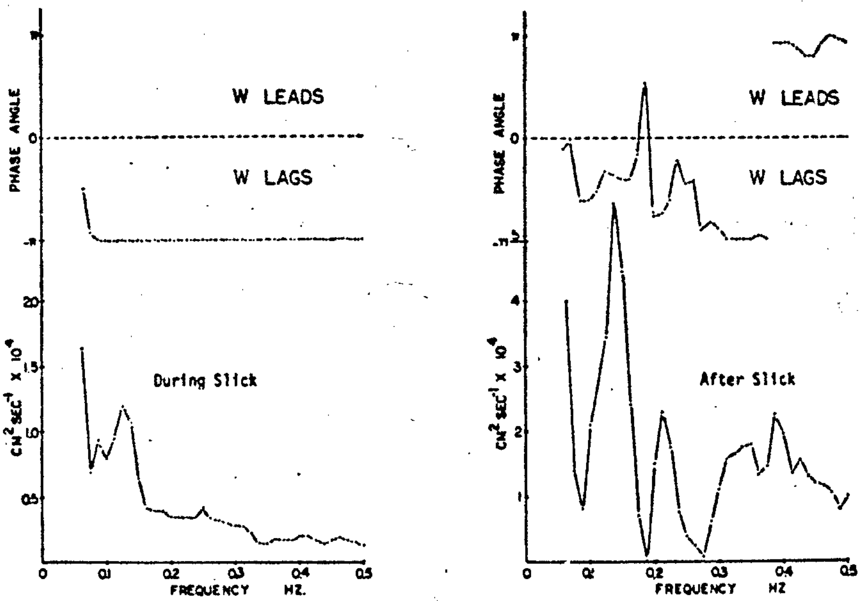

FIG. 5. Cross-spectral density U vs W.

of sea slick. Without the slick, however, the horizontal velocity maximum occurs over the wave trough. With the slick present, the horizontal velocity maximum shifts to over the wave crest.

2) The coherence between the short-wave (high frequency) components of the sea and the wind field directly above the water surface is strongly influenced by the presence of the slick. With the slick absent, there is a moderate coupling of the wind and the sea. When the slick is present, the wind field appears to lose all knowledge of the motions of the sea. This can be seen in the U and W vs η coherence plots and also in the U vs W phase angles. The phase angles of the Reynolds stress spectrum are completely unaffected by the underlying sea surface when a slick is present.
3) The horizontal velocity (Fig. 3) is a maximum over the wave trough for all frequencies. This result was first observed by Seesholtz (1968). At that time some had argued that such might be true only for low-frequency components or high-frequency components, but not both. Fig. 3 shows this phase relation to be true for both.

In considering the spectra, note that the instrument elevation lies below Miles' (1957) "critical layer" for the low-frequency spectral components. As the frequency increases, the critical layer for each wave component moves through the instrument height to lower levels.

6. Conclusions

The presence of a surface slick damps small surface waves, results in an increase of wind speed over the slick, and decreases the profile roughness length.

Since there was a decrease in energy of the dominant wind-driven sea, we also conclude that the slick interferes with the mechanism of generation of wind waves

The forces exerted on the sea surface by the atmosphere do work on it and generate wind waves. The reactions of these forces act on the atmosphere to generate turbulence. This process appears to depend on the existence of capillary wave systems. The introduction of the oleyl alcohol sea slick, with its strong damping and suppression of capillary waves, appears to completely destroy this process. This effect can particularly be noted in Fig. 5. When a slick is present, the U-W phase angle and Reynolds stress spectrum for the atmosphere appear to be completely unaffected by the undulating ocean surface directly below the sensor. With the return of the capillary wave systems, however, the atmosphere is strongly influenced by the entire spectrum of the underlying sea. This result suggests a need for the theoretical models of wind-wave interaction to consider the role of the capillary waves and strong coupling between very different scales of motion.

It would appear that laboratory investigations may be of limited value in wind-wave generation studies unless both the long wavelength gravity wave and the short wavelength capillary wave can be simultaneously scaled and represented in a laboratory environment.

These results demonstrate the importance of observing small-scale atmospheric processes near the ocean surface. The use of artificial sea slicks provides the field investigator with a powerful research tool. Their use constitutes one of the few measures a field researcher can employ to control his environment. It is strongly recommended that this technique be exploited to its fullest to enhance our understanding of the small-scale processes at the air-sea boundary.

The apparent importance of capillary waves and/or short gravity waves to air-sea dynamics is a matter requiring additional investigation, both theoretical and experimental. Before realistic models of the air-sea boundary processes can be constructed, the role of these waves in the total dynamics must be clearly identified.

Acknowledgments. This research was supported by the Office of Naval Research under Contract Nonr N00014-67-A-0204-0024, and by the National Science Foundation under Grant GA1439.

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